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Power management strategy in the alternative energy photovoltaic/PEM Fuel Cell hybrid system

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ABSTRACT

This paper deals with the control and management of a hybrid power system composed of two clean generators connected to the load via a DC-Bus. The system configuration can solve certain problems inherent to reliability and power supply quality emanating from generators renewable energy resources based connected to the load. Since the primary natural energy resource cannot be easy to handle due to fluctuations appearing at the output. This can be solved by using an adequate control strategy including intermediate energy storage. The paper describes some research works achieved till now in hybrid energy system area, including the assessment of the modeling and control methods used and a survey of control problems which must be carried out. The main contribution in this paper focuses with modeling the hybrid PV/PEMFC energy system, using Matlab/Simulink, optimizing a hybrid system devices using artificial intelligence and carrying out simulation studies using a real climate data and practical load profile. A comprehensive results of simulation showed that the model is effective, operational and that backup system composed of PEM Fuel Cells and electrolyser can be integrated with photovoltaic power systems to provide uninterrupted high-quality power.

Contents

1. Introduction

Energy is vital for the preservation of the life in the world; it expresses the economic stability of populations. It is fundamental to improve quality of life by the exploitation of natural resources. The unconcerned exploitation of these resources affects the environment on which these systems develop. The energy problem is thus synonymous to environmental and economic problems. The efforts must, consequently, have the obligation to find an optimal solution for the sustainable energy supply. The world's demand of energy increased in an exponential way, and on the other hand, the conventional energy resources are exhaustible and limited in the offer. Consequently, there is an urgent need to preserve what

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we have in hand and to explore the broader use of the alternative energy resources. Currently, more than half of the world's population of the developing countries live in the rural areas. The largest share of these populations makes use of fuels such as wood and agricultural wastes [1]. In addition, the lack of water could become one of the major concerns of humanity during this century. In certain parts of the world, climate warming will result in shortages of water and the dryness and deserts become increasingly large. Following a severe water shortage in two decades and meet to the increase in request [2,3]. Algeria has begun looking for a dynamic solution by promoting non-conventional water resources, such as desalination of brackish water.

Several works were carried out for the hybrid energy system production within the framework of sustainable development. Ghosh et al. propose a probabilistic model of simulation of autonomous systems Wind-Diesel (without batteries) based on the use of statistical data of loads and the swiftness of the wind [4]. Other authors describe the progress made in the hybrid systems Photovoltaic-Wind-Diesel in terms of electronic control systems (voltage regulators and frequency of the diesel generators and the wind mills), various experiments of hybrid systems in various places of the world, as well as the tools for simulation of these systems [5].

Several authors studied the behavior of the systems Photovoltaic-Wind-Diesel in [6]. In [7] the effect of the management of the energy demand in the systems PV-Wind-Diesel is studied in details. In this paper real and practical data are used for modeling and managing the PV–PEM Fuel Cell hybrid system, as well as the simulation of a management strategy of the flow energy with Matlab/Simulink is proposed. An overall power management strategy is designed for the system to coordinate the power flows among the different energy sources.

2. Hybrid systems

In the PV–PEM Fuel Cell hybrid system, the renewable PV power is taken as the primary source, one of the generators is a photovoltaic module and the other is a PEM Fuel Cell (Proton Exchange Membrane Fuel Cell) fed out of hydrogen where energy can be stored in the hydrogen form playing the role of backup and storage system. It should be noted that the two generators can function in parallel, thus, contributing to the global energetic efficiency. The sizing of PEM Fuel Cells system can be made up on the basis of a very simple calculation of the number of PEM Fuel Cells type necessarily laid out in series and/or parallel to answer the nominal output of the load. The boost converter is used here to adapt the whole PEM Fuel Cells output voltage to the DC-Bus voltage. In this study, the output voltage of DC-Bus is maintained to 220 V. According to the characteristics of the PEM Fuel Cell, it is found in the area of concentration with a current load of 15 A to avoid this zone and to leave a safety margin of operation. Operation point is selected around 10 A that gives a tension V_{pemfc} of 24 V. Thus, to approach a tension of 220 V at converter DC/DC input, the required number of PEM Fuel Cells is:

$$N_s = \frac{\text{PEM Fuel Cell system voltage}}{\text{PEM Fuel Cell stack voltage}} = \frac{220\,\text{V}}{24} = 9 \tag{1}$$

The number of PEM Fuel Cells stacks in series to compile 20 kW PEM Fuel Cells is:

$$N_p = \frac{\text{PEM Fuel Cell system power}}{\text{PEM Fuel Cell stack power}} = \frac{20\,\text{kW}}{9 \times 500\,\text{W}} = 5 \tag{2}$$

Thus, PEM Fuel Cell in the hybrid system is arranged as 9×5 stacks ((1) and (2)).

Electrical energy generated from various preliminary resources is controlled by auxiliaries controller artificial neural network What confers on the system is a hybrid behavior; since the configuration changes with each time, when one or the other of the resources is used for supplying the load; for example, the structural configuration is different if the electrolyser is working or not. The whole PV–PEM Fuel Cell system is composed of elementary devices which are automatically reconfigured when the conditions change. In addition to an auxiliary controller for each conversion system, there must be a high level controller which deals with the total strategy operation of all the system, according to the external variables such as the environmental and climatic conditions (solar radiation, temperature, etc.). This makes it possible for the modules to start up and to stop when necessary, thus changing the dynamics of the system.

The system dynamics are determined by the dynamics of both generators (the photovoltaic module and PEM Fuel Cell system) and of the control strategy. The disturbances are the solar radiation (and other variables of environment such as the temperature) and state of the load, while the output is the electric output (required by the load).

Very few efforts are presented for hybrid energy management to the level production facilities and are not found on in optimization approach [8–11]. The diagram of a PV–PEM Fuel Cell hybrid energy system for stand-alone application is indicated in Fig. 1. The system is constituted of photovoltaic generator, optimization device, power interfaces, and energy storage backup including an electrolyser, PEM Fuel Cell system and load unit. The relative tendencies with the availability of DC-Bus tension are carried out by means of electronic converters. In addition, the storage power devices have immense possibilities in near future.

3. Management of energy power systems

In multi-source alternative energy systems, an overall control strategy for power management among different energy sources is fundamental. Each combination of physical components of the hybrid system has an optimal control strategy, i.e., a way to manage the energetic (power) flow between different components with optimal approach and with the more low costs of possible operation by taking into account the useful components lifespan. Each control strategy is carried out for discrete numerical values of the various control variables. The control strategy determines how to manage flow energy. For each hour of time, according to the values of the weather variables, a load energy consumption (DC/DC converter and/or hydrogen production) and the energy storage device states (batteries, hydrogen tank), the control strategy determines which components must function and which not, where must one store energy "excess" surplus or which device must provide overdrawn energy to supply the load [12,13].

All these strategies have a basic principle the use of renewable sources to supply the request for potential consumption, using the excess energy to charge the batteries, to produce hydrogen or to feed the auxiliary components [14]. If the instantaneous request (power requested less power produced by the renewable sources) is negative, i.e., excess power produced by the renewable energy sources, then the surplus power is used to charge the batteries (or other accumulators). If the batteries are loaded to the maximum and the continuous excess of power, it is said whereas there is an excess of energy. In the case where the net request is positive, i.e., it is not sufficient with the renewable energy sources to answer the entire load requested, then the backup devices are used to supply the load if this one has an insubstantial load.

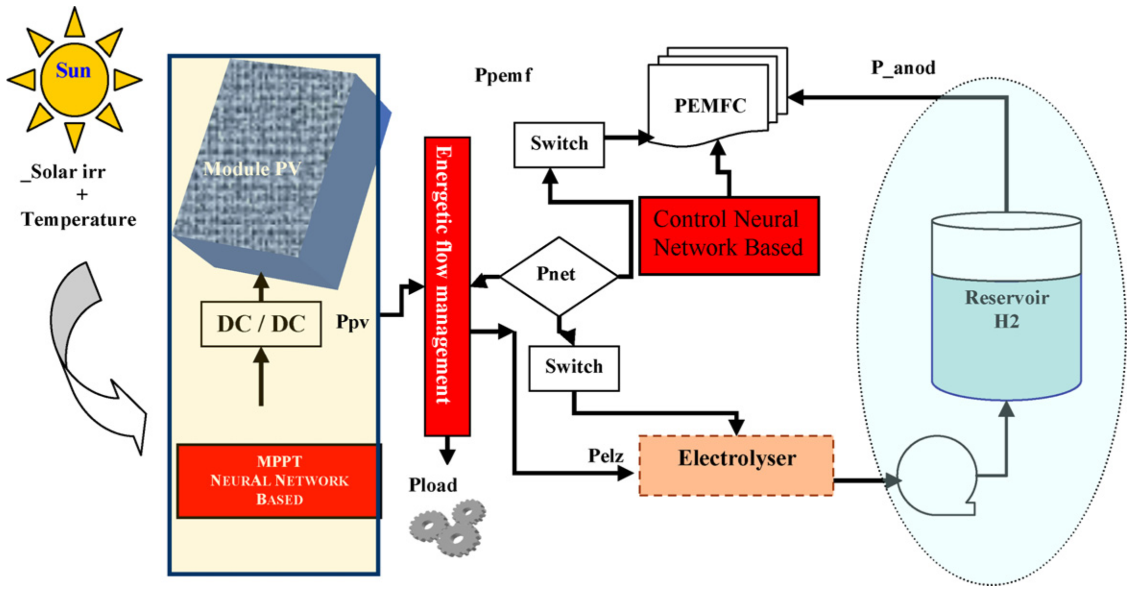

Fig. 1. Diagram of PV–PEM Fuel Cell hybrid system.

4. Photovoltaic/PEM Fuel Cell hybrid system

4.1. Introduction

A photovoltaic electricity generation converter system, controlled by MPPT (Maximum Power Point Tracker) neural network is the main renewable energy source of the system. The dynamic model of each component of the system was developed in [20]. The dynamics of the two generators (photovoltaic module and PEM Fuel Cells) are very different; the photovoltaic module shows a very fast behavior since the electricity generation is carried out on the level of the solar cells almost instantaneously. The dynamics of the PEM Fuel Cells is slow and its modeling is still a field open to research [15].

The primary goal is to develop the detailed and comprehensive dynamic model under Matlab/Simulink of each component of the hybrid system (PEM Fuel Cells, photovoltaic module and electrolyser). Once the validated models, the auxiliary controller models have were developed using artificial neural network approach (not discussed in this paper) [20]. It also developed a simulation of the hybrid energy system suggested PV–PEM Fuel Cell under Matlab/Simulink. Fig. 2 shows a global diagram of the simulation model under Matlab/Simulink. The overall control strategy for managing the power flow between the various energy sources in the system is discussed in the following section. The system performances under various operating conditions are thus carefully planned and evaluated.

4.2. Artificial neural network approach of MPPT

Photovoltaic power generation requires so much larger initial cost compared to other power generation sources that it is imperative to extract as much available solar energy as possible from the PV array. Maximum power output of the PV array changes when solar irradiation, temperature, and (or) load levels vary. Control is, therefore, needed for the PV generator to always keep track of the maximum power points. By controlling the switching scheme of the inverters connected to the PVs, the maximum power points of the PV array can always be tracked. Such a controller is implemented by neural network approach in this study. Nonlinear *I–V* characteristics of a PV module match very well to a neural network application. A multilayer feed forward perceptron-type NN is proposed for controlling the MPPT. The network consists of inputs, two hidden layers and an output layer. The number of neurons in the hidden layers would be determined by trial and error. The neurons in the input layer of the neural network get the input signals from the measurement of irradiance and ambient temperature, achieved by data acquisition systems each 5 min. The neurone in the hidden layer receive data from the input layer, calculate their outputs using the sigmoid activation function, and then pass them to the second hidden layer finally to the neurons in the output layer. The sigmoid function is written as

$$y_j = \frac{1}{1+e^{-x_j}} \tag{3}$$

The neural network outputs are the data values of the neurons in the output layer. The neural network, using solar irradiation and ambient temperature as inputs, generates switching control signals to the DC/DC converters. The neural network output is a duty cycle, used to adjust the converter switching scheme (Fig. 3).

In the training process of the neural network, a set of input–output training data is needed. These training data are obtained from data acquisition system. The set of input–output training data consists of 300 patterns. One data acquisition each 5 min implies that we have data for one entire day. The data were kindly provided by UERAR Ghardaïa. Updating the weights of the neural network is performed using the Levenberg Marquardt algorithm with the steepest descent method. This algorithm tries to minimize the sum of the mean squared errors.

In order to simulate the system, the photovoltaic model described above implemented in Matlab/Simulink is submitted under real conditions of irradiation and temperature, and then delivers photovoltaic array current corresponding. Designed neural network controller was defined and designed using neural network toolbox. The system was simulated for a complete day with real sources power data collected by data acquisition system.

Output of the artificial neural network controller is a duty cycle that controls switching of DC/DC power interface and adapts the output power to required load demand. Simulation studies have been carried out to verify the proposed artificial neural network method.

The maximum power points are depicted in Fig. 4 for both Perturb and Observe method and for the artificial neural network

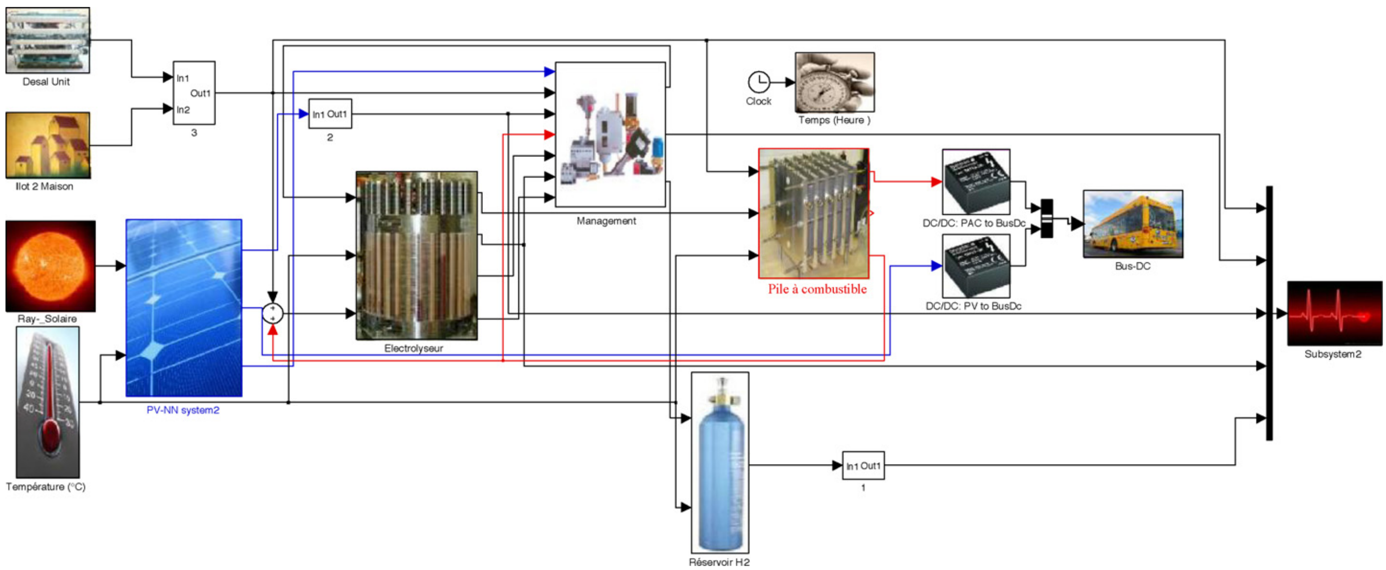

Fig. 2. Diagram block of the hybrid system developed under Matlab/Simulink.

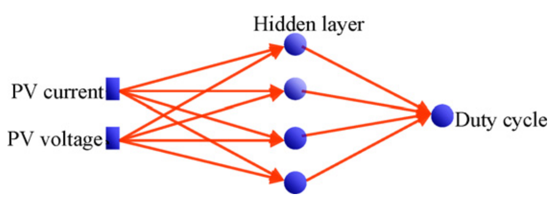

Fig. 3. Artificial neural network MPPT.

controller issues. This shows that the artificial intelligent method tracks very well the MPP under various climate conditions.

The artificial neural network, which stores two sets of weighting values and thresholds, creates appropriate switching signals to the boost converter so that the PV array can always generate the maximum available solar energy. In the Perturb and Observe algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, ΔP, is observed. If the ΔP is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP [20].

Artificial neural network maximum power point tracking presents best results under experimental and real weather conditions. Maximum power point is tracked accurately. In order to design and validate the controller, a complete model of the photovoltaic system was elaborated. This model is composed of a sub-model for each individual component of the system. It was possible to determine that the controller effectively behaves as expected, meaning that it was able to maintain an adequate output power for load demand.

A major assumption made in simulations is the use of an ideal DC–DC converter, as opposed to a more realistic model that includes losses. The model, however, should provide sufficient results for verification of MPPT functionality. However, artificial intelligent approach is better than best classical method to track the MPP.

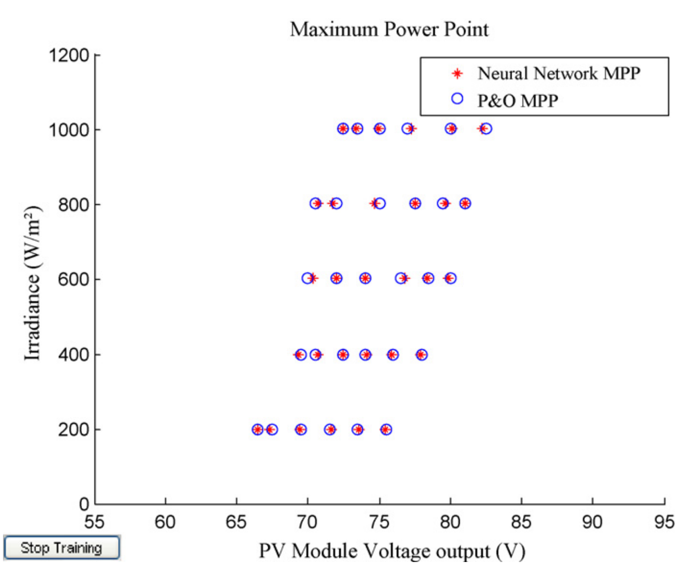

Fig. 4. Maximum power points at different irradiance and different temperatures.

4.3. The load (requested power)

In this paper and in addition to a small islet of four houses, a water desalination unit using a reverse osmosis process is regarded as load. Until today, the brackish desalination water units were used in extreme circumstances despite the strong energetic consumption by the process. The electrical power required six components for the unit which mainly consists of pump water transfer, the acid dosing system, the filter scaling substance system, the degassing system, the cartridge filter and two high pressure pumps. The brackish water is pumped with a storage tank and is treated. The high pressure pump applies permanently the necessary pressure to overcome the osmotic pressure of water and the drop pressure of the system, and the feed water is pumped into the reverse osmosis system [16,17].

The load profile of the desalination unit using a reverse osmosis process during one day is given in Fig. 7, in dark yellow and dotted lines. The peak load of the desalination unit during the day is 6.59 kW occurring between 9 a.m. and 11 a.m. At 8 a.m. the request for load is 0.8 kW, between 12 noon and 15 p.m the required load is of 3.45 kW. For the remainder of the day, the load is null. The amount of a global energy required by the load over one year is

12,730 kWh. The production of drinking water of 20 cm^3 per day during five operating hours per day is carried out with a brackish water desalination unit with a lifespan of 10 years [18].

4.4. Hybrid system Photovoltaic/PEM Fuel Cell control strategy

The conversion system photovoltaic generator adapted by the MPPT is the independent energy source of the system. The difference in power between the source generation and the load request is calculated by:

$$P_{\text{net}} = P_{\text{PV}} + P_{\text{FC}} - P_{\text{load}} - P_{\text{aux}} \tag{4}$$

where P_{PV} is the power generated by the photovoltaic energy conversion system. P_{FC} is the power generated by the energetic conversion system PEM Fuel Cells.

P_{load} is the load power and P_{aux} is the consumption by auxiliary components that ensure optimal system operation. In this paper, only the electrolyser power flow P_{elz} is considered as consumption $P_{\text{aux}} = P_{\text{elz}}$.

4.5. Power management strategy

The control strategy objective is to produce electrical energy according to the needs for the load, prone to the constraints and the dynamics of the physical load (brackish water desalination unit, dwelling, etc.) by distributing the energy demand between the photovoltaic field and the PEM Fuel Cells system. In the hybrid configuration considered, the photovoltaic field prolongs the possibilities of designed control on the distribution of a current proportioned with the load via a control system of the constant current supply starting from the alternative resources [9,19].

The control problem can be established as: to achieve a certain electric demand (reference) using produced energy coming from the photovoltaic module or the PEM Fuel Cells or the combination of both. In order to use the PEM Fuel Cells, part of the energy which is produced by the solar module must be previously stored as hydrogen by using the electrolyser and the tanks.

The control strategy applied here is that at every given moment, the surplus of power produced by the photovoltaic module (4) is provided to the electrolyser to produce hydrogen which is stored in the suitable tank via a gas compressor. The governing control strategy is that at any given time, any excess photovoltaic generated power is supplied to the electrolyser to generate hydrogen that is delivered to the hydrogen storage tanks through a gas compressor. Thus, the balance equation of power can be written as:

$$P_{\text{PV}} = P_{\text{load}} + P_{\text{elz}}, \quad P_{\text{net}} > 0 \tag{5}$$

where P_{elz} represents the electrolyser consumption to produce hydrogen. When there is deficit in the power production (6), the PEM Fuel Cell starts to produce energy for the load by using the hydrogen stored in the tank.

The power balance equation can thus be written as:

$$P_{\text{PV}} + P_{\text{FC}} = P_{\text{load}}, \quad P_{\text{net}} < 0 \tag{6}$$

where P_{FC} is the power generated by the PEM Fuel Cell system.

A high level control must handle discrete variables (switches electrolyser and PEM Fuel Cells to start and stop) and continuous variables (production of hydrogen and the current provided by the PEM Fuel Cells) which contribute to the generation of reference energy desired. The inputs of the controller are calculated depending on the internal state of the hybrid system and the load request.

The strategy control can be formulated as follows:

The objective is to reduce the cost function which tracks the desired power reference using the PEM Fuel Cell as less as possible along the day. Subject of the constraint is that the hydrogen tank must be kept between its lower and higher limits (pressure). The photovoltaic module provided electrical energy to the load, and the PEM Fuel Cell on the stop.
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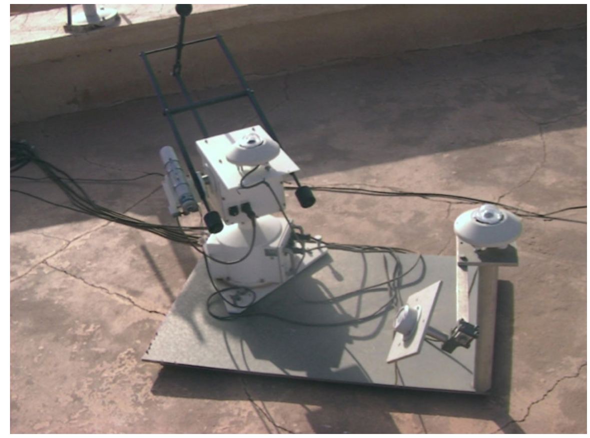

Fig. 5. Data acquisition system.

Let us note that during the change of the work conditions (climate, energy request), the system can evolve to any operating process.

5. Simulations results

In order to carry out a simulation of the hybrid energy system, photovoltaic/PEM Fuel Cell, the inherent data to the energy request (load) and the climatic data (solar radiation, temperature) are necessary. Here, the system is designed to supply electric power to a small islet of houses and a water desalination unit. A practical profile of load is used for a simulation study. For the needs to suitability, the profile of load request is given along one day of 24 h. The realistic climatic data (solar radiation and temperature) are performed, in Algeria site, collected with an acquisition system located in Ghardaïa (Fig. 5) are used in this simulation. The equipment is able to measure the solar radiation and the ambient temperature. The simulations studies are carried out for the power management during the typical day of the winter. The load request is also taken in winter for the small islet of houses and the water desalination unit. The simulation results of the winter scenario and its analysis are given and discussed, and interesting conclusions are announced. The daily data of the solar radiation and the temperature collected at 5-min time intervals, during the December 21st, 2006 are presented in Fig. 6 [20].

6. Simulation results of hybrid energy system photovoltaic/PEM Fuel Cell management strategy

The system efficient under the climatic data, as well as the load profile indicating the electric power request by a small islet of houses and a water desalination unit of capacity of 20 cm^3 per

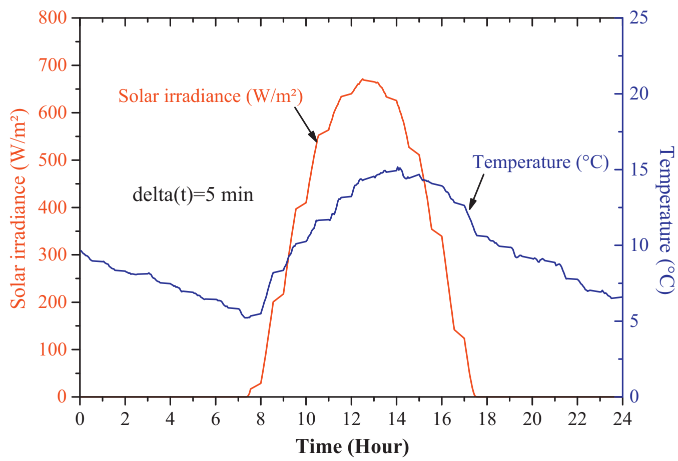

Fig. 6. Radiation and temperature of the 355$^{\text{ième}}$ day of 2006 in Ghardaïa.

days given in Fig. 7, is evaluated and discussed below in terms of quantization of hydrogen tanks storage out which represents an inescapable index of appreciation and the primary reason of the hybrid energy system PV–PEMFC existence.

The output power of photovoltaic module is controlled by a maximum power point tracking method (MPPT) neural network [20]. When, $P_{\text{net}} > 0$ (5), there is excess power available for the hydrogen production. Fig. 8 shows global irradiance and electric energy provided by the photovoltaic module. The power available is used by the electrolyser to produce hydrogen. Fig. 9 characterizes the PEM Fuel Cell output power in call of total load request and the power available for the electrolyser to provide hydrogen necessary to the power supply of the PEM Fuel Cells for this application. Fig. 10 shows variations of the hydrogen tank pressure for the 24-h period of simulation with a 1 h step of time interval.

The analysis of these variations clearly expresses the performances of the management strategy adopted to carry out the supply of the energy required by the load while saving the resources in stored hydrogen form. Lastly, all powers concerned come into play in the management of the hybrid system suggested are illustrated in Fig. 11.

The hydrogen tank pressure varies according to the hydrogen flow at input and the output. It results that the pressure of the storage tank increases when it has excess power available for the production of hydrogen and decreases when the PEM Fuel Cells provided electricity to the load and consumes hydrogen.

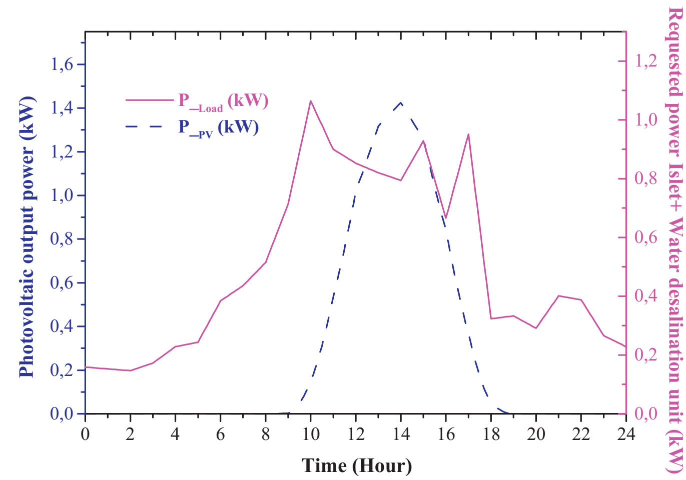

Fig. 8. Power delivered by photovoltaic module and the request load in winter (kW).

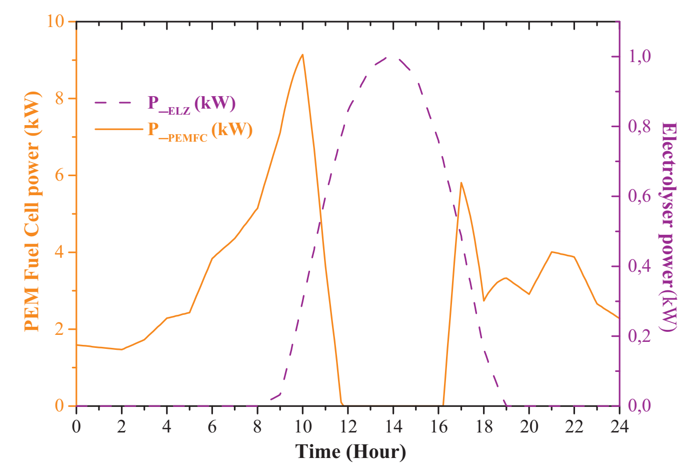

Fig. 9. Production and consumption powers of the hydrogen in winter (kW).

When $P_{\text{net}} < 0$, (6), the power generated emanating from the photovoltaic module is not sufficient to satisfy the load request; under these conditions the PEM Fuel Cell starts to supply the power deficit. Fig. 10 shows also the power deficit which must be supplied to the PEM Fuel Cells, where hydrogen amount is consumed and consequently the power delivered by PEM Fuel Cell.

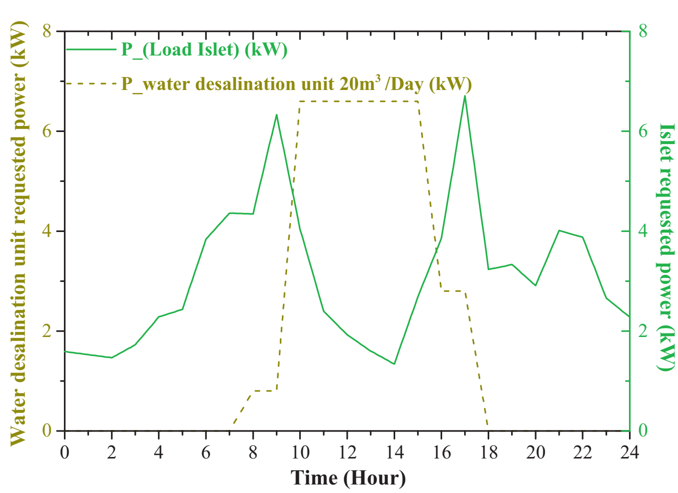

Fig. 7. Profiles of requested power by a small island + water desalination unit (kW).

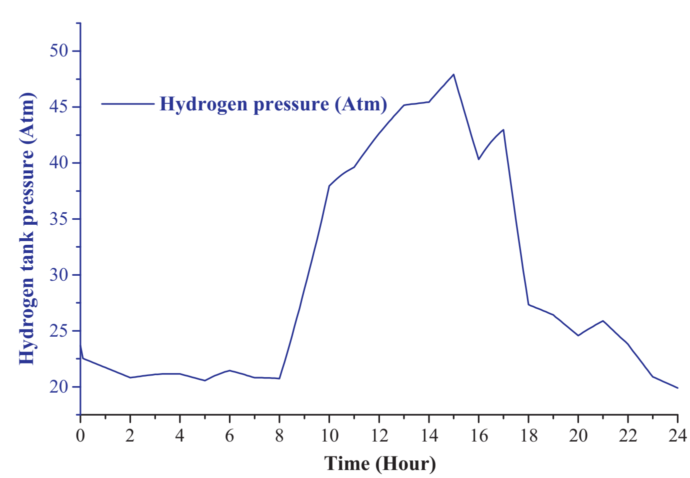

Fig. 10. Hydrogen tank pressure available in winter (atm).

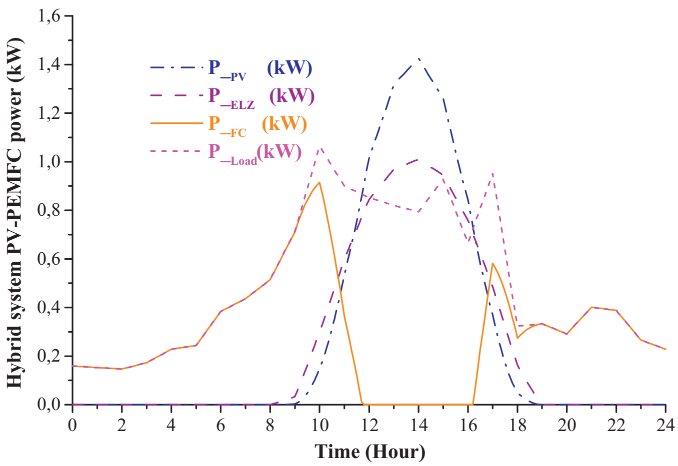

Fig. 11. Hybrid system PV–PEM Fuel Cell Power.

7. Conclusions

In this work a management strategy of the hybrid energy system PV–PEMFC is presented. The photovoltaic system is the principal electrical generation device. The electrolyser works as an energetic backup by feeding surplus energy to produce hydrogen. The PEM Fuel Cell system is the secondary electrical generator which works for satisfying the deficit of power required by the load and contributes to energy balance between the power provided by the photovoltaic module and the total load (small islet of houses and water desalination unit). The results show that the management strategy of the energy flow in a hybrid energetic system PV–PEMFC is effective through the various energy sources (solar or hydrogen vector) and required load of the energy flow is managed successfully using heuristic algorithm. The replacement of conventional technologies; by the hydrogen technology including, PEM Fuel Cell in the systems of electrical power for the isolated sites and small industry based on renewable energies is technologically feasible in Algeria sites, which reduces the emission of effluents, the dependence of oil and increases the integration of renewable energies. Hybrid systems composed of PEM Fuel Cell and electrolyser can be integrated with PV power systems to provide uninterrupted high-quality power. Energy can be stored and recovered starting from the hydrogen tank filled by the electrolyser which is supplied by the excess energy coming from the solar radiation. However, the study shows that the research and technological development in the field of the PEM Fuel Cell and the electrolyser are more than necessary; much efforts are necessary, because with the improvement of the output of both PEM Fuel Cell and electrolyser, it is possible that the hydrogen vector will settle definitively and quickly in the world energy order.

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